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THE LOS AZUFRES, MEXICO, GEOTHERMAL RESERVOIR: A CASE HISTORY

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Los Azufres is the second geothermal reservoir that has been developed in Mexico. It is located in the Mexican Volcanic Axis, about 90 km East of the city of Morelia, the capital of the state of Michoacán. The field sits atop the Sierra de San Andrés range, covering about 30 km². Currently there are about 50 wells, drilled to depths ranging approximately from 600 to 3500 m. Seven wells feed the current installed capacity of 25 MWe, which soon will be raised to 75 MWe. The current plans contemplate an installed capacity of 210 MWe for 1989. Considerable effort has been invested in exploration and developed of this resource. This work succintly describes the exploration, development, and assessment of the field. It begins with the exploratory phase, based on geologic, geophysical and geochemical techniques, which were found reasonably efficient and cost-effective. Exploratory and developmental drilling, and the corresponding results are also discussed. We comment on the drilling strategies used during exploration and development. The last part of this work deals with the assessment of the reservoir. We describe the reservoir engineering techniques used for assessment, their advantages and pitfalls in relation to this particular field, the corresponding results, the development of conceptual and numerical models of the reservoir, etc. Finally, we describe the experience obtained in this field with the use of portable back-pressure generators. This case history will be of value and interest to countries and/or companies engaged in the development of new geothermal resources in South America.

Los Azufres é o segundo reservatório geotérmico que tem sido explorado no México. Ele está localizado no Eixo Vulcânico Mexicano, aproximadamente 90 Km a leste da cidade de Morelia, a capital do Estado de Michoacán. O campo está localizado no topo da terra de San Andrés e cobre cerca de 30 Km². Atualmente existem cerca de 50 poços perfurados com profundidades no intervalo de 600 a 3500 m. Sete poços alimentam a atual capacidade instalada de produção de 25 MWe, que deverá ser elevada brevemente para 75 MWe. Os planos atuais prevêem uma capacidade instalada de 210 MWe para 1989. Um esforço considerável tem sido investido na exploração e desenvolvimento deste recurso. Este trabalho descreve sucintamente a exploração, desenvolvimento e avaliação do campo. Ele se inicia com a fase de exploração baseada em técnicas geológicas, geofísicas e geoquímicas, as quais foram consideradas razoavelmente eficientes e com boa relação entre custos e resultados. Perfurações exploratórias e de desenvolvimento, com os resultados correspondentes também são discutidas. Comenta-se sobre as estratégias de perfuração durante as fases de exploração e desenvolvimento. A parte final deste trabalho trata da avaliação do reservatório. Descreve-se as técnicas de engenharia de reservatório usadas na avaliação, suas vantagens e desvantagens em relação a este campo em particular, os resultados correspondentes, o desenvolvimento dos modelos conceituais e numéricos do reservatório, etc. Finalmente, descreve-se a experiência obtida neste campo com o uso de geradores "back-pressure". A descrição deste caso será de valor e interesse para países e/ou companhias envolvidas no desenvolvimento de recursos geotérmicos na América Latina.

(Traduzido pela Revista)

INTRODUCTION

In this work we attempt to summarize the experience accumulated during the exploration and development of the Los Azufres geothermal field. The accent is heavily on the practical side. Thus, highly interesting academic matters are left out; however, the extensive reference list at the end of the paper will help the interested reader in that respect (though the references list is by no means complete). Los Azufres, located in a Quaternary volcanic setting, is expected to present useful similarities to other geothermal fields of Latin America, either known or yet undiscovered, especially those located in volcanic Andean terrain. For that reason, this case history will be of value and interest to countries and/or companies engaged in the development of new geothermal resources in South America.

Los Azufres is the second geothermal reservoir that has been developed in Mexico. It is located in the Mexican Volcanic Axis, about 90 km East of the city of Morelia, the capital of the state of Michoacán (Fig. 1). The field sits atop the Sierra de San Andrés range, covering about 30 km² (Fig. 2). Its altitude ranges approximately from 2700 to 3500m a.s.l.; the surrounding valleys are several hundreds of meters below the mean altitude of the field. Currently there are about 50 wells, drilled to depths ranging approximately from 600 to 3500m. Seven wells feed the current installed capacity of 25 MWe, which soon will be raised to 75 MWe; the current plans contemplate a second enlargement of the installed capacity to 220 MWe, for 1989 (Alonso, 1985). Considerable effort has been invested in the exploration and development of this resource. Its development, updated to early 1985, is summarized by Quijano (1985). A review of multidisciplinary studies carried out to assess the reservoir is presented by Nieva et al. (1986).

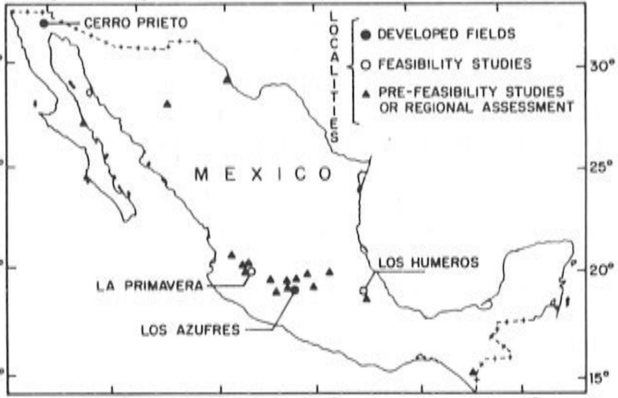

Figure 1 — Location of the Los Azufres geothermal field in México, and its relation to other geothermal sites in different stages of exploration and development.

Geothermal exploration and development is generally regarded as consisting of 5 classical (e.g., Olade, 1978) stages: reconnaissance, prefeasibility, feasibility, development and exploitation. The first 3 stages are collectively refered to as exploration. Reconaissance applies to the national and regional level; its goal is to select relatively small (500 - 2000 km²) areas of specific geothermal interest for further study. Prefeasibility aims to identify smaller zones (reservoirs?), typically 10 - 100 km² in area, where deep exploratory wells can be located. Feasibility starts simultaneously with drilling of the first deep exploratory well; its main goals are to delineate the

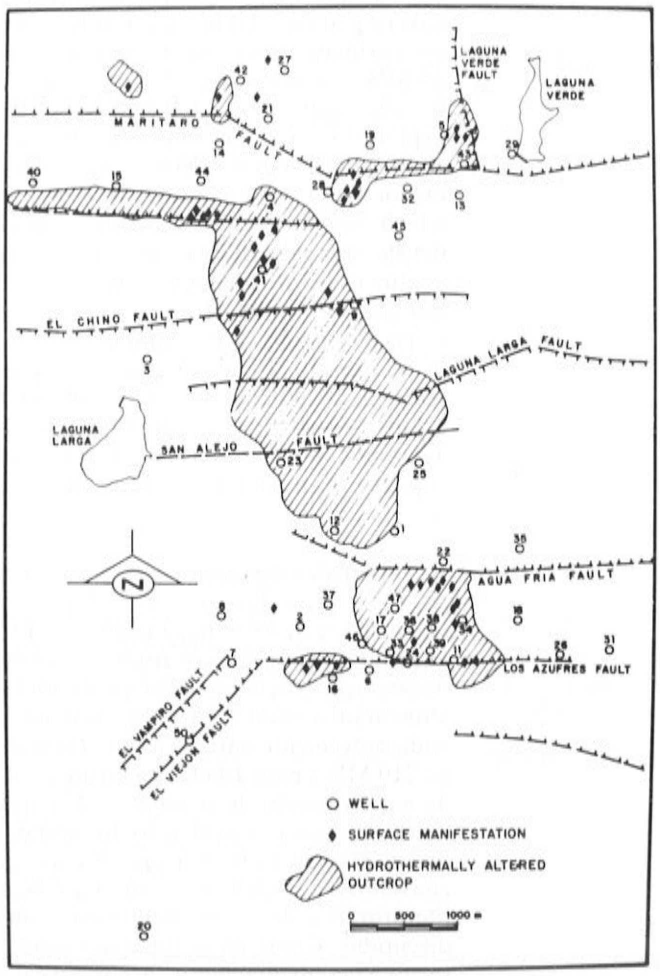

Figure 2 — General map of the Los Azufres geothermal field.

geothermal field, and to reliably assess the recoverable reserves of heat and mass, and their deliverability. Development begins when a sufficiently reliable model of the reservoir is available; its main goal is to set up the necessary infrastructure for commercial exploitation of the field. In practice, there is often a good deal of juxtaposition of some of these stages, due to technical, economic or political reasons. For example in extensive geothermal fields, such as The Geysers (U.S.A.) and Cerro Prieto (México), the pattern has been that feasibility studies on a part of the reservoir are completed, and development is started and perhaps completed in that part, before feasibility studies on other parts of the reservoir are completed or even started. This pattern is observable also in Los Azufres, due partly to its relatively large areal extent, and partly to the particular geohydrological characteristic of this reservoir. Thus, in this paper we have lumped together the feasibility and development stages.

This work succinctly describes the history of the exploration and development of the Los Azufres geothermal field. The paper is organized in sections that sequentially deal with reconaissance, prefeasibility/development, and exploitation. The emphasis is on the techniques that proved most successfull, from the practical point of view, in each of these stages.

RECONNAISSANCE

For Los Azufres, this stage took place before 1975. The area was well known for its fumarolic activity and thermal waters long ago (e.g., the German naturalist Alexander von Humboldt visited this area in his trip to Mexico in 1803-1804). Furthermore, topographical, geological, hydrological and meteorological regional maps, as well as aerial and satellite photographs were available before 1975.

The geothermal provinces of México were described by Mooser (1964). Them, Razo and Puente (1965) performed an early regional geological survey, specifically designed for geothermal exploration, which included Los Azufres. About 10 years later, another regional geological study (Demant *et al.* 1975)[1], was comissioned by Comisión Federal de Electricidad (The Mexican Electrical Utility, hereafter CFE) also in the area of Los Azufres, to assess its geothermal possibilities. This can be considered the last reconnaissance study.

PREFEASIBILITY

Analysis of the early geological information metioned in the preceding section, and a detailed geological survey at the local level (Camacho & Palacios, 1976) led to the definition of a small potential area of about 300 km² (typical values range between 500 and 2000 km²) for prefeasibility studies. Two important factors that helped narrow down the size of the selected area were the presence and locations of surface manifestations (fumaroles, hot springs, hydrothermally altered outcrops, e.g., Fig. 2), and the location of the field on a topographic high, many kilometers away from the next cluster of surface manifestations. Geochemical analysis of the fluids from the surface manifestations provided early estimates of reservoir temperatures and of their areal distribution (Molina, 1975; 1976; Molina & Templos, 1978). These estimates proved accurate, by exploration standards, when compared with later, more detailed results obtained after many wells had been drilled. In these early studies, temperatures were estimated by means of the Na/K (Fournier & Truesdell, 1970) and Na-K-Ca (Fournier & Truesdell, 1973) geothermometers for liquid samples; and by means of the modified Lyon-Hulston geothermometer (e.g., Molina & Templos, 1978) for gaseous samples.

Prefeasibility studies also included an independent fotogeologic survey (Electroconsult, 1976, unpublished), and resistivity vertical soundings (CFE, 1975, unpublished; described later by Romero and Palma, 1983).

FEASIBILITY/DEVELOPMENT

This stage began with the drilling of the first deep exploratory well, Az-1, in November 1976. This bore, completed in September 1977, turned out to be the discovery well. The siting of Az-1 was decided on the basis of resistivity anomalies found in geoelectric surveys, complemented with surface structural geology data, and geochemical results that indicated high underground temperatures at the site (Garfias & González, 1978; the rest of the data quoted in this paragraph is from the same authors). The well was drilled to a total depth of 2173m. The maximum temperature measured in the shut-in well was about 290°C, a very good prospect. Flow tests demonstrated that the well produced 24 ton/hr of fluid [63% steam, 37% liquid, at a separation pressure of 2.2 bar(g)] via a 5 in ϕ O.D. slotted liner. For a relatively small-diameter exploratory well, this production was considered promising. Moreover, the quality of the produced heat turned out to be high grade, appropriate for production of electricity. The lithology of the formations traversed by the borehole as inferred from drill cuttings and cores; it showed a stack of 3 main andesitic flows, a 20m thick kaolinized zone believed to correspond to the intersection with the plane of the Agua Fria fault, and several fractured zones of varying permeabilities. The well produced from the deepest fractured zone.

About 3 months after the completion of the discovery well, a second well (Az-2) was spudded 1140m to the SW of Az-1. The siting was decided on the basis

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[1] When considering epochs in the case history and dates of the references, remember that the results of any studies are usually known well in advance of the corresponding publication date.

of the existence of a low resistivity (5 ohmm) anomaly, geochemical results indicating temperatures of 250°C at depth, and aiming to intercept the Puentecillas fault at a depth similar to that of the production zone of Az-1 (Garfias, 1979; the rest of the data quoted in this paragraph is from the same author). Drilling was terminated at a much shallower depth, however, because an important feed zone was intercepted at 1130m. This production zone was later correlated to the intersection of the El Viejón fault. The maximum temperature measured in the shut-in well was in excess of 275°C. Flow tested, the well produced 300 ton/hr of a 39% steam, 61% wate misture, at a separation pressure of 7 bar(g). The generation capacity of this well was estimated to be about 10 MWe.

From then on, the pace of the drilling operations accelerated. The drilling history of the field is condensed in Fig. 3. The shape of these curves depends on many variables, including: the difficulties found and the results obtained in each new well; the results and interpretations of studies on different disciplines and their evolution with time; feedback between results, interpretations and decisions, that conduct to new results; logistics; economics; financial constraints; etc. The breakdown of the total (cumulative) number of wells completed each year in producers, injectors, abandoned and low-permeability wells reflects some of these variables. The wells labeled abandoned were lost due to uncontrolable drilling problems arising from mecanical failure of the rock around the borehole; none of these wells reached depths greater than a few hundred meters. The curve depicting injection wells reflects both, ecological concern about the safe disposal of spent brine, and the discovery of low-performance wells. The curve corresponding to low-permeability wells reflects the considerable degree of difficulty encountered in this field to locate producing zones, which is related to the fractured nature of the reservoir.

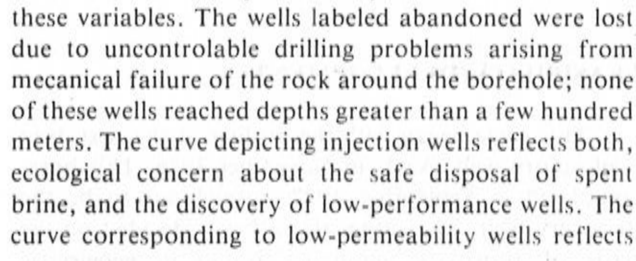

Figure 3 — History of deep geothermal drilling in Los Azufres.

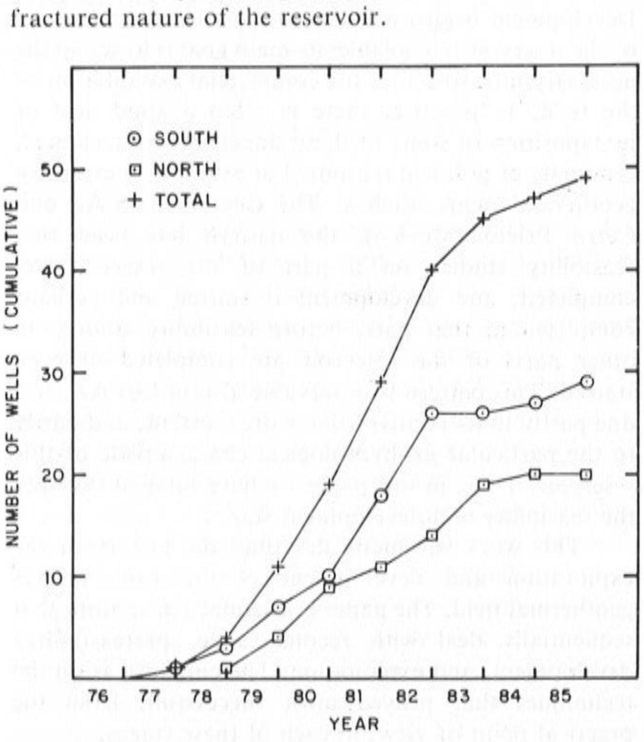

Figure 4 — Drilling history of the southern and northern portions of the field.

In Fig. 4 the total (cumulative) number of wells completed each year has been broken down into southern wells and northern wells, in order to convey a sense of the areal dimension of the drilling history. The limit between the northern and the southern portions of the field has been taken as an E-W line that pases to the North of wells Az-23 and Az-25, and to the South of well Az-3 (see Fig. 2). This subdivision of the field is consistent with the shape of the reservoir (as deduced from resistivity, drilling, petrological, geochemical and reservoir engineering data), which presents two shallower zones known as Maritaro in the North and Tejamaniles in The South, which are joined at depth (see Fig. 5). This information about the detailed shape of the reservoir evolved mostly from knowledge made available through drilling of new wells, though early resistivity surveys did show northern and southern lowresistivity anomalies separated by a resistivity high (Fig. 6). Fig. 4 reveals that exploratory and developmental drilling in the southern portion of the field generally preceded that taking place in the northern portion of the field. This happened mainly because a relatively shallow, high-enthalpy zone of the reservoir was discovered in Tejamaniles, in the neighborhood of wells Az-6 and Az-17 (see Fig. 2), which produced mostly steam; this zone was considered economically and ecologically convenient for early development. Thus, development of the southern portion of the field took precedence, as hinted in the Introduction.

In the subsections that follow, we attempt to summarize the technical studies performed since the

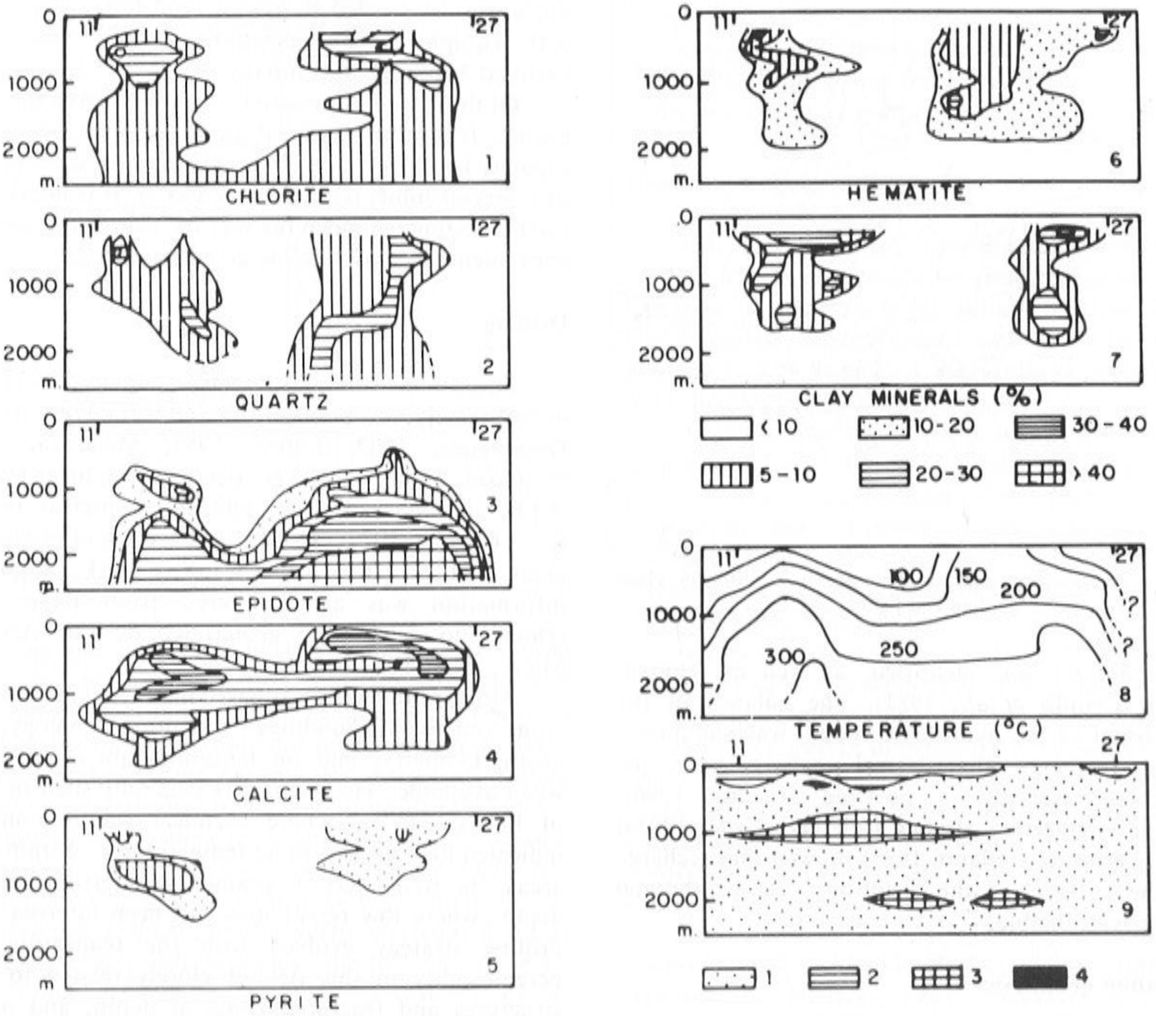

Figure 5 — N-S section of the reservoir, as revealed by hydrothermal alteration mineralogy (segments 1-7), temperature (segment 8) and petrographic units (segment 9). Numbers assigned to petrographic units are as follows: (1) microlithic andesite; (2) rhyolites and ignimbritic tuffs; (3) porphyroblastic andesite; and (4) dacite. (after Cathelineau et al., 1985).

begining of the Feasibility/Development stage, and their main results, and stress the techniques that proved most successful, from the practical point of view.

Geology

Detailed geological studies included a vulcanological survey (Pasquaré *et al.,* 1977), the definition of faults and fault structures by aerophotogeological interpretation (Camacho & Ramirez, 1978); field surveys to define surface geology (e.g., Camacho, 1979); K-Ar dating and paleomagnetic investigations (Aumento & Gutierrez, 1980); extensive studies of the petrology and associated hydrothermal alteration of drill cores and drill cuttings(Combredet, 1982; Gutierrez & Aumento, 1982; Cathelineau *et al.*, 1985); other studies of structural geology (De la Cruz *et al.*, 1982; Garduño & Martiñon, 1985); fission-track dating of obsidians (Gutierrez & Lopez, 1983); volcanic stratigraphy and geochemistry (Dobson, 1984); etc.

Structural geology turned out to be of great importance, for its inmmediate applicability for sitting new wells, because the fault systems in the field (e.g., Fig. 2) are closely associated with teh distribution of permeability at depth. Petrological studies contributed a great deal to the 3-D delineation of the reservoir (e.g., Fig. 5), and provided useful clues to the presence of high temperature horizons at depth.

Hydrology

There were two main studies of this complex region, located in the intersection of 3 hydrological basins, with locally widely variable altitude and rates of precipitation, evapotranspiration and runoff. A deep

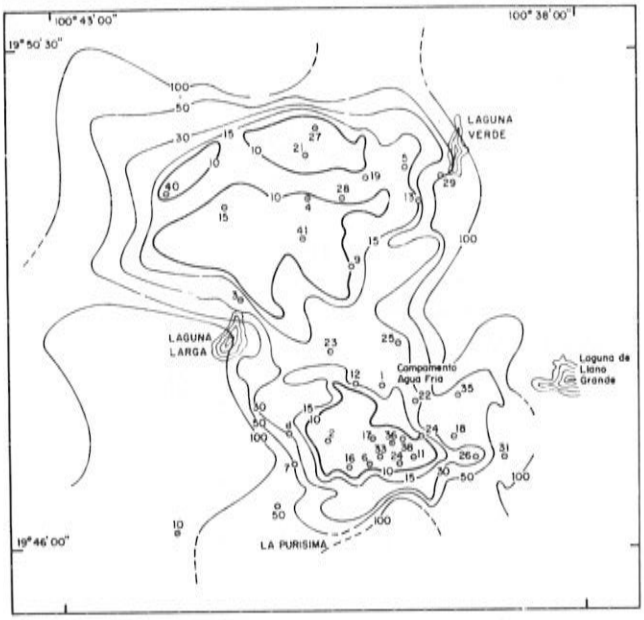

Figure 6 — Isoresistivity curves (ohm-m) at AB/2 = 1000 m, plane view (after Romero and Palma, 1983).

regional aquifer was identified, as well as regional gradient (Cedillo *et al.*, 1981). The balance of the input/output of the hydrologic system was computed, providing evidence that lateral recharge into the geothermal reservoir is possible (Lachs, 1986). Reservoir engineering studies (Iglesias *et al.*, 1985a, 1985b; Iglesias & Arellano, 1985) showed that recharge from the surface of the field into the geothermal reservoir is negligible.

Exploration geophysics

Geophysical studies included determination of gravity anomalies (J. Romero De León, 1982, private communication), monitoring of microseismic activity (A. Reyes, 1983, private communication), magnetometry (e.g., see Garfias & González, 1978), and a number of resistivity surveys (Razo *et al.*, 1978; Romero, 1982; Palma, 1982; Arroyo, 1982; Romero & Palma, 1983). Furthermore, when the first well was drilled, several types of wireline logs were run; unfortunately, the interpretation of these logs faced difficulties associated with lack of proper calibration with respect to volcanic rocks, and with the effects of the high temperatures prevailing in the well (Ponce, 1977). Currently, the use of modern wireline logs is being seriously considered agian, on the basis of the useful results yielded by recent field tests, carried out with equipment and personnel from Pemex, the national Mexican oil company.

Of these studies, resistivity surveys proved the most useful, from the practical point of view, for their capacity for delineation of target zones for drilling, and of reservoir limits (e.g., Figs. 6 and 7). It is hoped that further testing will open the way for the regular use of a convenient suite of wireline geophysical logs.

Drilling

Specific to this all-important activity, there are, unfortunately, few publications and formal reports (e.g. Domínguez, 1983; López, 1983; Mendoza, 1983; Mendoza, 1986). However, detailed graphical records (CFE, unpublished) and detailed geological reports (e.g., Garfias, 1979) exist for each well, and provided a great deal of information for this work. Important information was also gathered from Reyes S.R. (Desarrollo del campo geotérmico de Los Azufres, Mich., unpublished).

Siting of the wells was based mainly on information from resistivity soundings, strucutural geology, and geothermometry, and on fence-diagram correlations, when available. The wells were generally sited in areas of low resistivity, where chemical geothermometers indicated high underground temperatures. Within these areas, the wells were programed to intersect faults at depths where low resistivities had been inferred. This drilling strategy evolved with the realization that peremeability in this field is closely related to fault structures and fractured zones at depth, and mostly does not correlate with the type of formation drilled.

The typical completion of wells in Los Azufres is illustrated in Fig. 8. The typical set up of the well head assembly is shown in Fig. 9. This configuration evolved to reduce mechanical problems associated with high temperature-induced stress in the casing.

Typical drilling problems found in this field include lost circulation, cave-ins, stuck drillstrings, trapped drillstrings, fishing, cratering, blowouts, and deviation control. Lost circulation has been often controlled by decreasing the density of the drilling mud, and adding standard obturants. To prevent cave-ins and associated drillstring trapping, special care has been exercised in

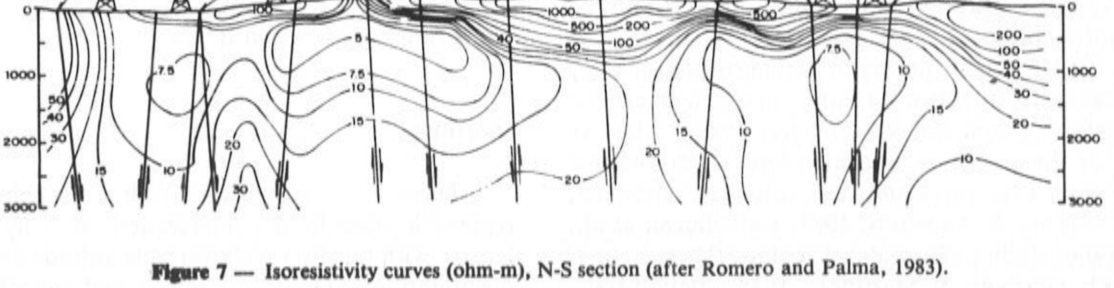

Figure 7 — Isoresistivity curves (ohm-m), N-S section (after Romero and Palma, 1983).

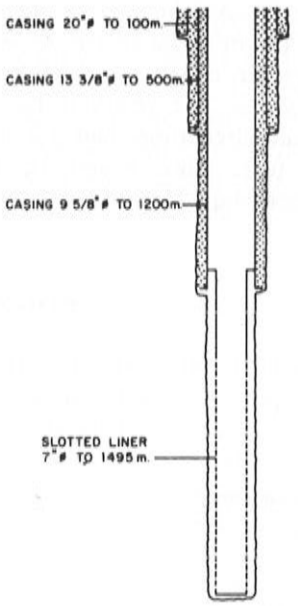

Figure 8 — Typical completion of wells at Los Azufres.

adjusting the properties of the drilling fluid to the prevalent type of formation and temperature, and controling the drilling time in each stage. To prevent stuck drillstrings, the tools are mantained in constant movement, drill piping is connected extra fast, drilling mud is energetically homogenized with an intense circulation, etc. Fishing problems arise mostly because of the high temperatures prevailing in the wellbores, which severely limit the standard fishing techniques; this has been one of the hardest problems confronted in Los Azufres. Several wells were lost due to blowouts (e.g., Fig. 3) and one well (Az-24) due to a cratering event. The hard, volcanic rocks predominating in Los Azufres (andesites, rhyolites, dacites) often present sudden hardness contrasts, due to severe hydrothermal alteration, that tend to cause unwanted deviations while drilling; this problem has been curbed by using special bottomhole assemblies in which the drill bit is helped by 3 stabilizers (e.g., Fig. 10).

Geochemistry

Many geochemical studies (e.g., Molina & Templos, 1978; Molina *et al.*, 1980; Templos & López, 1980; Giggenbach & Quijano, 1981; Templos & Laredo, 1980; Nieva & Quijano, 1982; Nieva *et al.*, 1984; Rodriguez *et al.*, 1984; Nieva *et al.*. 1985; Kruger *et al.*, 1985; Quijano, 1985a; 1985b; Nieva *et al.*, 1986) based on the chemical composition as well as on stable isotopic compostions of the fluids produced by wells and surface manifestations, have been performed during this stage. This work helped delineate the 3-D thermal structure of the reservoir, played and important role in the definition of the thermodynamic conditions of the unperturbed reservoir fluid, and contributed independent and very important evidence of the existence, location and characteristics of an extensive two-phase zone overlaying a deep compressed-liquid reservoir. The importance of the geochemical work for exploration and characterization of this field cannot be overemphazised.

Sampling of radioactive radon gas in the surface of the field gave promising results for mapping conductive faults and fractures (Gutiérrez and López, 1983).

Reservoir Engineering

This discipline bears the ultimate responsibility for the resource. A great deal of reservoir engineering work has been carried out on behalf of Los Azufres. Unfortunately, an important fraction of it has not been published. The summary that follows includes both published and unpublished work.

Field work included mainly pressure and temperature profiling of the wells, running transient pressure tests, performing short- and long-term production tests, running tracer tests, performing shortand long-term injection tests, and, recently, thermohydraulic stimulation of low permeability wells (Aragón, 1986, unpublished).

Assessment of individual wells in the field included analysis of stabilized temperatures (e.g. Jaimes, 1983a); of pressure/temperature profiles (CFE, numerous unpublished reports); of production output curves (e.g., Iglesas & Arellano, 1985); of transient well tests (e.g., Jaimes, 1983b; 1984; Iglesias & Arellano, 1985); decline curve analysis (Iglesias & Arellano, 1985); analysis of reinjection performance (e.g., Suárez & Gutiérrez, 1983; Aragón *et al.*, 1984); etc.

Assessment of groups of wells, portions of the reservoir, and field-wide studies include tracer tests (Iglesias & Hiriart, 1981; Aragón A., private communication, 1983; Iglesias *et al.*, 1985d), evaluation of the unperturbed thermodynamic state of the reservoir fluids (Iglesias *et al.*, 1985a; Kruger *et al.*, 1985), development of a 3-D static model of the reservoir (De la Cruz & Castillo, 1984), development of a 1-D vertical model of the natural flow in the reservoir (Iglesias *et al.*, 1985b; 1986a), numerical simulation of the southern portion of the reservoir (Suárez & Jaimes, 1984); evaluation of petrophysical properties of reservoir formations (Contreras *et al.*, 1984; Iglesias *et al.*, 1985c; 1986b), etc.

A significant fraction of these studies involved the use, and in some cases the development, of sophisticated methodologies, without which the assessmnet of the reservoir would have been slower and less reliable. Furthermore, a lot of attention has been paid to the multidisciplinary nature of geothermal reservoir assessment; consequently, no efforts were spared to crosscheck models and results arising from different disciplines and perspectives, in order to maximize the reliability of the assessment. The feasibility studies mentioned in the preceding paragraphs were sometimes hampered by less-than-topquality data and by lack of enough and appropriate instrumentation for field measurements. On the other hand, the relatively early commissionning of 5 wellhead

5 MWe power plants provided a cost-effective and convenient way for long-term flow testing of a significant number of wells, in both main regions of the field. The positive results of recent thermohydraulic stimulation experiments offer a promising way to enhance the productivity of the field, and the costeffectiveness of drilling.

From the studies sketched above evolved a picture of a large (about 19 km³, with an area of about 32 km²) and complex reservoir, capable of producing 220 MWe for at least 20 years. The reservoir has two widely separated, vertical circulation had discharge zones, linked at depth (e.g., Figs. 5 and 7); a deep, hot (300°C), compressed-liquid zone is overlaid by a 2 —

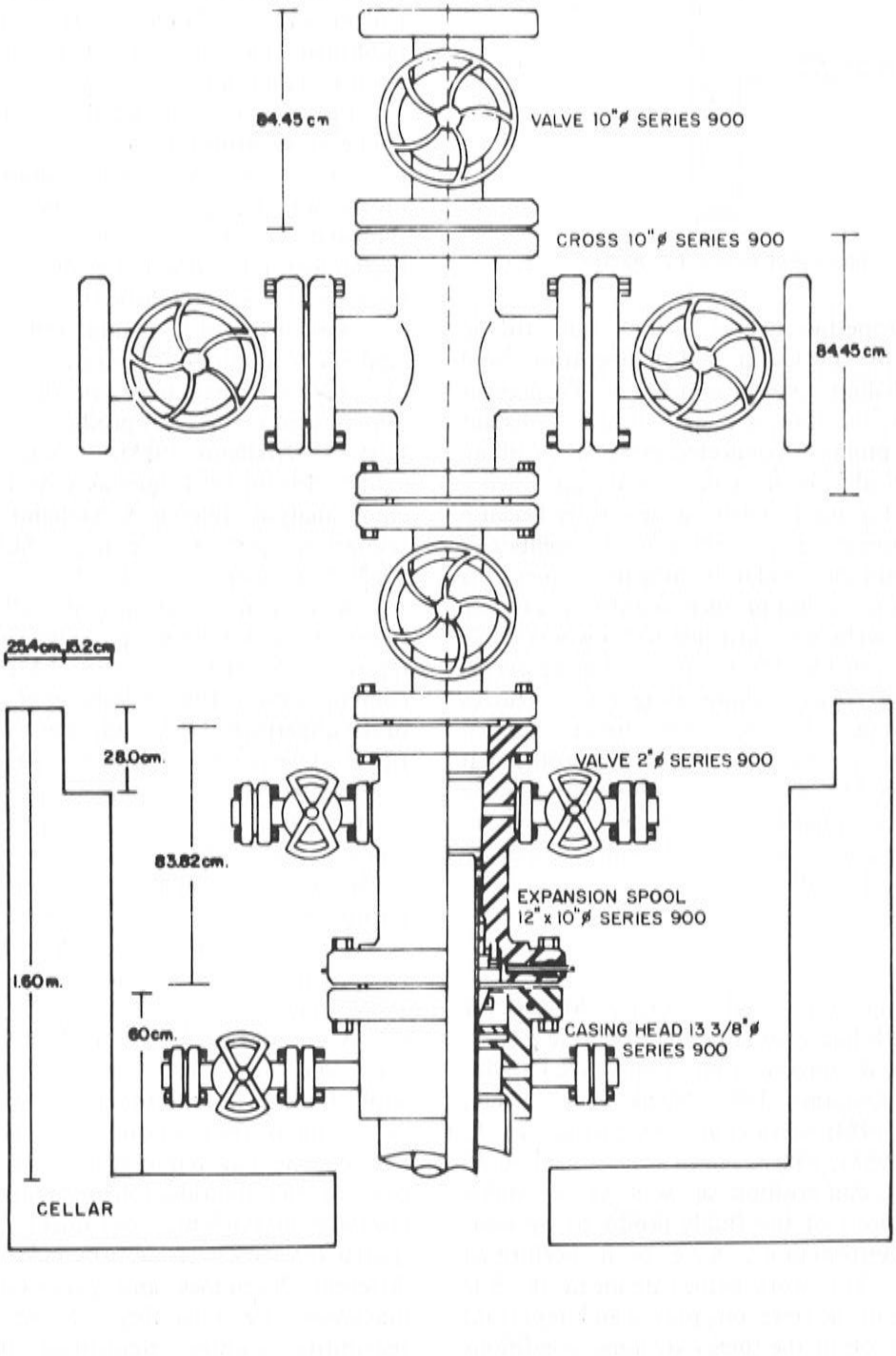

Figure 9 — Typical wellhead assembly.

phase liquid — dominated region, which in turn is overlaid by a vapor — dominated zone (Fig. 11); the distribution of permeability is associated with the conductive fraction of the fafult systems of the field. This highly complex set up results in production flowrates and enthalpies that very widely with the location and depth of the wells.

EXPLOITATION

Exploitation began in this field well ahead of the end of the classical feasibility stage. This happened because it was decided to use a set of 5 small wellhead power plants as a means to help assess the resource. This strategy proved particularly advantageous for Los Azufres, due to the complexities (see the preceding section) involved in evaluating the resource, and because revenue is being generated while the assessment process continues.

The portable, back-pressure, 5 MWe well head power plants are described, and their advantages and disadvantages are discussed, by Hiriart (1983). Briefly, the main disadvantages are a relatively high consumption of steam per KWh, increased vulnerability to lightning and high winds due to too many transmission lines, and uncontrollable discharge of geothermal gases to the atmosphere. The main perceived advantages are: a low capital investment in power plants; that generation can start well ahead of what would be possible with a central power plant; the possibility of using wells for which long-term production tests are unavailable; that well head units are especially atractive for units are especially atractive for wells with high gas content; the lower heat losses in steam pipes resulting from shorter distances to the wellhead; the oportunity to assess the resource while geneerating revenue; reliability (higher for 10 5 MWe units than for 1 50 MWe power plant); and simplified construction and engineering work. Furthermore, it has been shown (Hiriart, 1986) that, at least in Los Azufres, wellhead generation is economically competitive with central power plant generation.

The 5 wellhead units have been generating electricity for slightly less than 4 years now. They proved highly reliable. Initially, each plant was fed by one well. However, after a while it was necessary to reinforce the amount of steam being fed to units 1 and 5, by.

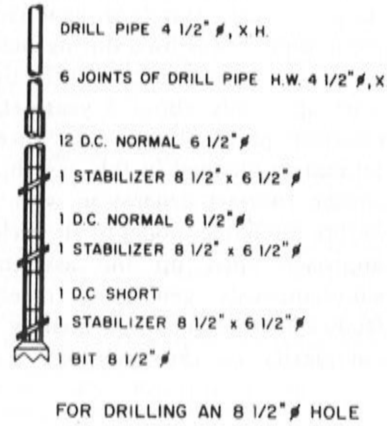

Figure 10 — Bottomhole assembly used for better directional control, showing drill bit and stabilizers.

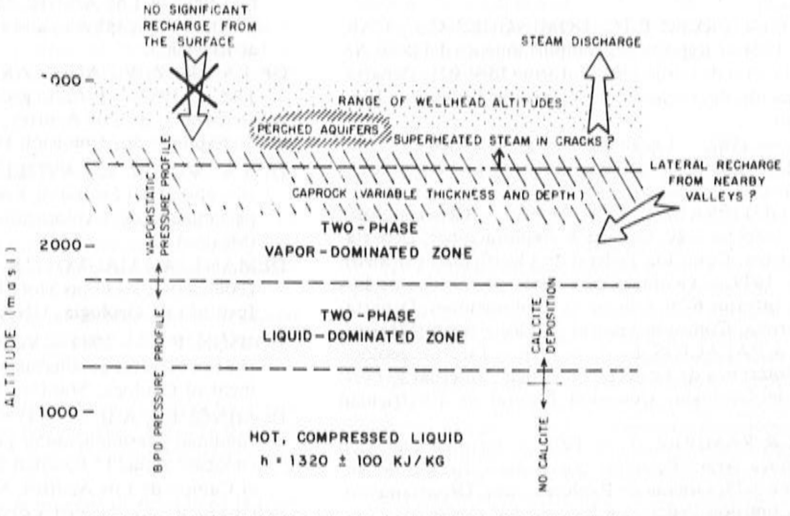

Figure 11 —Schematic 1-D vertical model of the reservoir (after Iglesias et al., 1986a)

connecting a second well to each plant, to avoid underuse of these units. The presence of these units allowed long-term production testing of 7 strategically located wells. The corresponding information proved invaluable for the assessment of the reservoir.

SUMMARY

Los Azufres is a major geothermal field that is expected to present many useful similarities with geothermal fields located in volcanic settings. Thus, this case history is of interest to parties involved in exploration and development of this type of geothermal resources in Latin America and elsewhere.

For Los Azufres, the combined effective time taken by the reconnaissance and prefeasibility stages was less than 2 years; standard geological and geochemical methodology was used during these stages.

From the completion of the first well, to generation start up , only about 5 years elapsed. However, the classical prefeasibility and development stages are intimately blended in this case history, because it was chosen to start generation with small wellhead units before a reliable model of the field was available. This approach sped up the assessment process, while simultaneously generating revenue. The feasibility studies have been complicated by the large size and the complexity of the reservoir, e.g., the permeability distribution is rather unpredictable, and resulted in a relatively high fraction on low permeability wells. In a promissing development, recent thermohydraulic stimulation experiments offer hope for enhancing the productivity of low-permeability wells. Several blowouts and one cratering event caused further delays in the feasibility stage. Special precautions had to be taken to diminish the risks and to enhance the efficiency of the drilling operations. Speedy and reliable assessment of this complex resource required highquality, sophisticated, multidisciplinary, state-of-theart methodology. Finally, for Los Azufres, wellhead units where found to be economically competitive with a central power plant.

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